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Influencing the arc and the mechanical properties of the weld metal in GMA-welding processes by additive elements on the wire electrode surface

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Abstract. Under the premise of an increasing scarcity of raw materials and increasing demands on construction materials, the mechanical properties of steels and its joints are gaining highly important. In particular high- and highest-strength steels are getting in the focus of the research and the manufacturing industry. To the same extent, the requirements for filler metals are increasing as well. At present, these low-alloy materials are protected by a copper coating (<1 µm) against corrosion. In addition, the coating realizes a good ohmic contact and good sliding properties between the welding machine and the wire during the welding process. By exchanging the copper with other elements it should be possible to change the mechanical properties of the weld metal and the arc stability during gas metal arc welding processes and keep the basic functions of the coating nearly untouched. On a laboratory scale solid wire electrodes with coatings of various elements and compounds such as titanium oxide were made and processed with a Gas Metal Arc Welding process. During the processing a different process behavior between the wire electrodes, coated and original, could be observed. The influences ranges from greater/shorter arc-length over increasing/decreasing droplets to larger/smaller arc foot point. Furthermore, the weld metal of the coated electrodes has significantly different mechanical and technological characteristics as the weld metal from the copper coated ground wire. The yield strength and tensile strength can be increased by up to 50 %. In addition, the chemical composition of the weld metal was influenced by the application of coatings with layer thicknesses to 15 microns in the lower percentage range (up to about 3 %). Another effect of the coating is a modified penetration. The normally occurring “argon finger” can be suppressed or enhanced by the choice of the coating. With the help of the presented studies it will be shown that Gas Metal Arc Welding processes are significantly affected by thin film coatings on solid wire electrodes for Gas Metal Arc welding. The influences are regarding the stability of the arc, the properties of the weld metal in terms of geometric expression, chemical composition and mechanical properties, the composition of the arc-plasma and the dynamics of the molten metal.

1. Introduction

In times of decreasing resources, lightweight high strength construction materials are getting important. Thus the mechanical properties of low alloyed high strength steels are more and more interesting. In particular the water-quenched and thermomechanically rolled fine-grained get propagated in many different applications in the manufacturing industry. To the same extend as the use of high strength steel increases, the demands on the weldability of these steels and the mechanical properties of the used filler materials are increasing. At present, these additional materials for GMA-welding are mostely protected by a copper coating or in rare cases a coating of titanium, brass or bronze against corrosion. In addition, the coating provides a good ohmic contact and good sliding

properties. These three characteristics form the three core requirements of current solid wire electrode coatings [1]. In this context arises the question whether other coating elements meet these requirements but also merge into the metal vapor of the arc plasma and into the melt pool and affect the process characteristic, the melt pool and the mechanical properties of the weld metal. This hypothesis is supported by the familiar effects of various alloying elements in steel melts and their segregates on the surface of the melt pool, also called Marangoni effect, [2]. The surface tension is a primary factor of influence in the formation of the melt pool dynamics and is changed by a variety of alloying elements of iron, [3]. In addition to the Marangoni effect, other influences on the formation of the penetration and the melt pool dynamics in GMA welding could be found. According to Takasu et al. [4], four forces are involved: a stirring force by the moment of the falling drop, a radial force by the normal percentage of the drop motion, a buoyant force induced by density differences between the droplets and the molten pool and forces due to the Marangoni effect. Furthermore, according to Mills [2] aerodynamic drag forces, and electromagnetic Lorentz forces resulting from the flow of current, have to be added.
A possible influence of the arc can also be based by known facts. The plasma, in which the arc passes, consists of proportions of the used welding gas and vaporized metal. The metal vapor has depending on its composition different ionization energies and this influences the shaping of the arc and the current transition, [5].
Apart from these effects, it is expected that a change of the mechanical properties and the solidification behavior of the weld metal by alloying the melt pool via the coating, occurs. By introducing finely divided nitrides or carbides, which act as solidification nuclei, a finer micro structure can be achieved. Due to the alloying elements and the micro structural changes, among other things, an increase in strength of the weld metal is expected [6], [7].

2. Preparation and characterization of test materials

For the preparation of coated wires, the physical vapor deposition has been used, as it allows a wide range of coating compositions. The base wire for the coatings was a copper-coated steel wire (DIN EN 14341-A G50 7 4Mo M21) designed for temperature steels. **Figure 1** shows the coating chamber used. During the coating process the copper-coating of the wire electrode was almost completely removed by a plasma etching process and had no influence on the welding experiments with the coated solid wire electrodes.

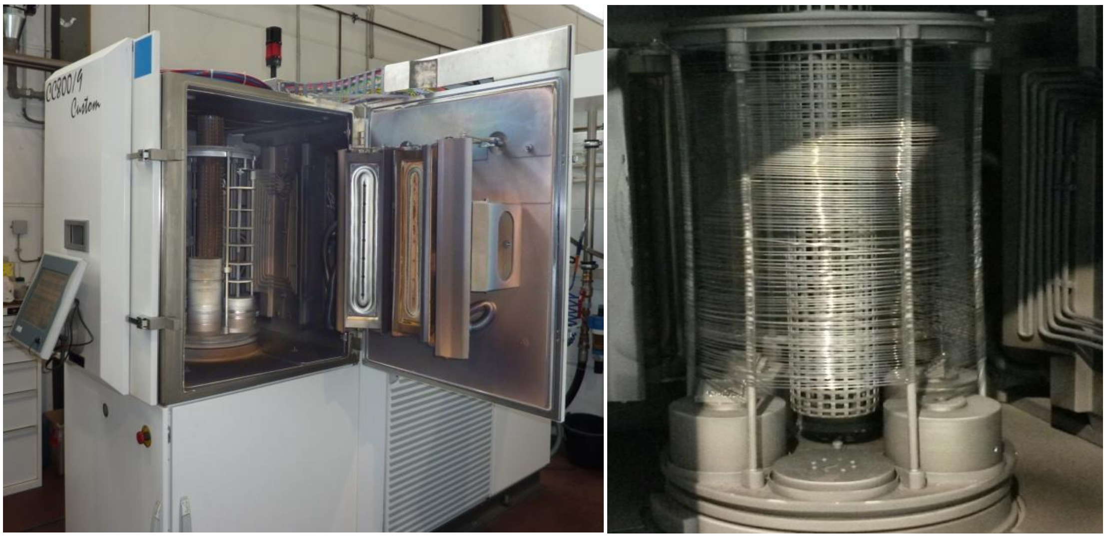

Figure 1. PVD system for coating of the wire electrodes

Figure 2 shows an example of a coating produced in the micrograph. In the lower region the etched structure of the steel wire can be seen. The individual layer thicknesses of each investigated coating system are listed in **Table 1**.

Table 1. Layer thicknesses

Coating system	TiN	Cr + C	Al + TiN	Al + Cr	NiCr + SiCr	Cr	Ti
Layer thickness in µm	4.5	2	4.5	16	6	8	15

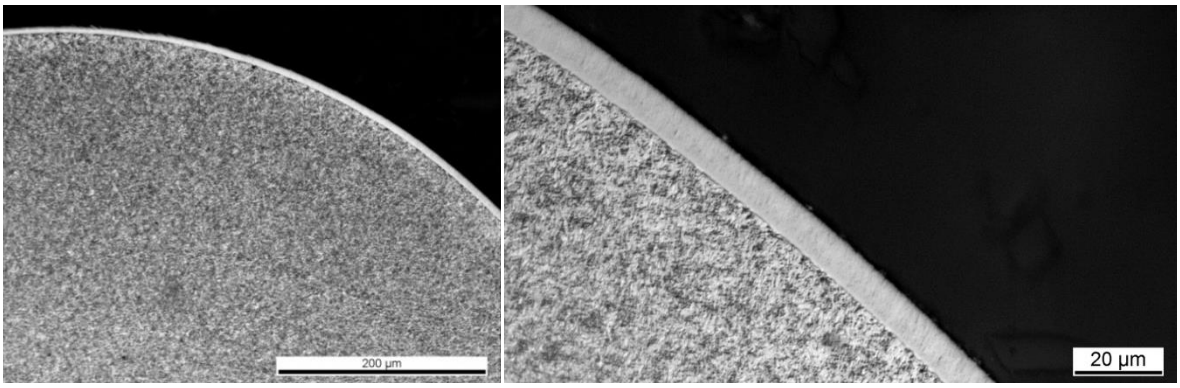

Figure 2. Ti-coated solid wire electrode

The welding processing of the coated wire electrodes with a GMA process was carried out at comparable process conditions. First dummy seams are carried out to assess the penetration behavior, followed by the creation of three-layer deposit-welding for taking spectroscopy and tensile specimens. The welding tests were carried out on the fine grained steel S700MC.

3. Influence of arcing, penetration behaviour and mechanical properties

To detect the influences on the welding-arc, high-speed imaging of the arc and the droplet transition were performed. The imaging clearly shows that influencing the arc and the droplet transfer can be done via the coatings. As an example, the pictures of the welding arc in argon and in 82 % + Ar 18 % CO_2 atmosphere under the use of the copper coated base wire and chromium- respectively titanium-coated welding wire are shown in **Figure 3**.

Pictures are taken during welding with comparable power and voltage values. The different arc-length for the different coatings can be seen clearly in Fig. 3. Using Ti-coatings the arc has been significantly extended. It is even visible that the arc begins to form the typical shape of a rotating arc.

Using a mixed gas (82% Ar, 18% CO_2) a similar behavior can be observed, **Figure 3**. It differs only in the absence of the rotating arc using the Ti-coating. Furthermore, the recordings show that the chromium coating resulting in a huge drop which performs a transition without short-circuits.

In summary, titanium content in the coatings leads to an extension of the arc-length and chromium content is accompanied by a shortening of the arc.

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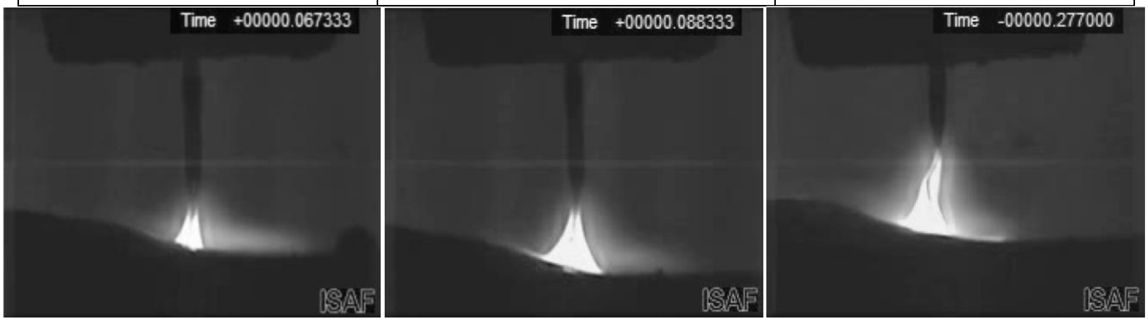
Shielding gas: Argon		
Cr-coating	Reference	Ti-coating



Shielding gas: 82 % Argon + 18 % carbon dioxide		
Cr-coating	Referenz	Ti-coating

Figure 3. Comparison of the arc length, under argon, and mixed gas (82 % Ar + 18 % CO_2)

In addition to an altered arc behavior, the impact of the wire electrode coating on the penetration behavior was found and investigated. In **Figure 4** the penetration behavior for the various coatings is shown. A change in the shape of the weld metal penetration can clearly be seen. Some coatings such as TiN or Al + Cr suppress the normally occurring argon finger. In contrast, the Cr + C coating increased the argon finger. The most visible change could be achieved by the coating of pure titanium. The penetration was wider and the weld metal shows a significantly flatter transition between weld and base metal. Further, the argon finger is less pronounced than in reference weld metal formed by the coppered wire electrode.

In addition to the shape of the weld penetration also the chemical composition of the weld metal was changed by the coating on the solid wire electrode. To quantify the chemical composition of the weld metal it was determined by optical emission spectroscopy for the three-layer deposit weldings. In order to prevent a possible influence on the measurement results by contamination on the sample surface, the samples were abraded before the tests.

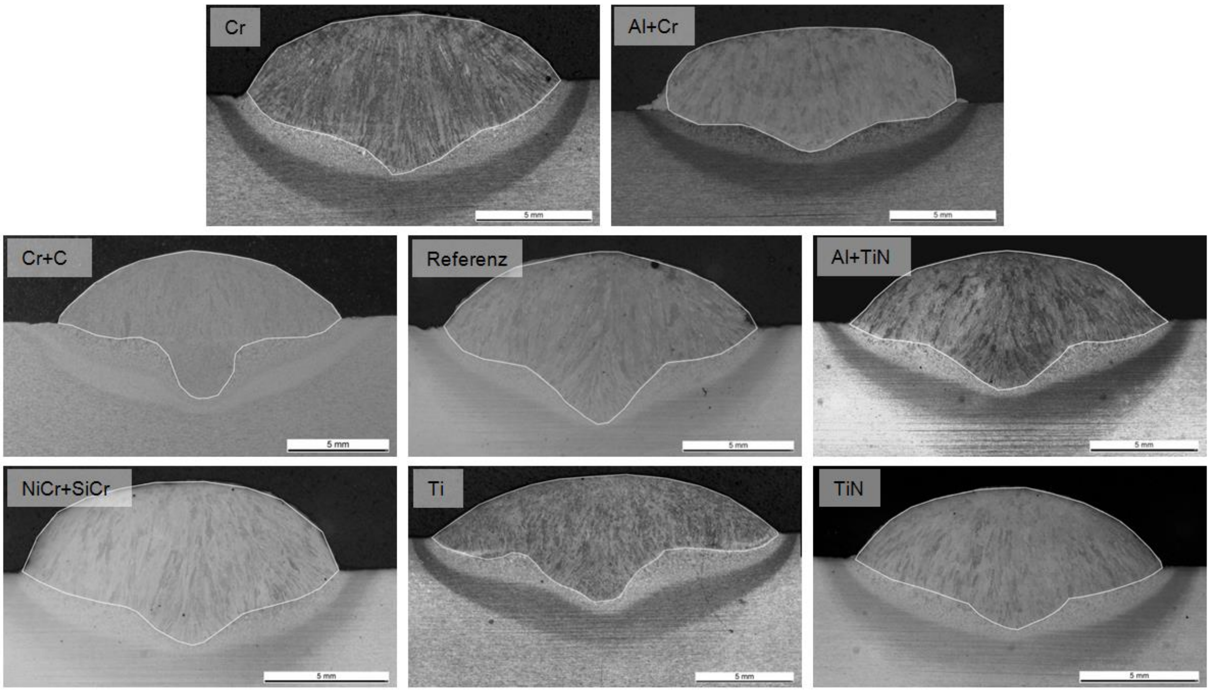


Figure 4. Penetration behavior

After the abrading, the measurement point is located approximately 2 mm below the original sample surface. It turns out that all elements of the coating pass into the weld metal. An increase in the corresponding mass contents can be clearly seen, *Tab. 2*.

Table 2. Mass content of the weld metal for various elements (selection)

Layer	Mass contents in %					
	Al	C	Cr	Ni	Si	Ti
4Mo (Referenz)	-	0.07	0.10	0.07	0.59	-
TiN	-	0.07	0.21	0.07	0.63	0.54
Cr + C	0.01	0.12	0.56	0.08	0.46	-
Al + TiN	0.29	0.08	0.1	0.07	0.66	0.25
Al + Cr	0.37	0.09	2.39	0.07	0.65	-
NiCr + SiCr	-	0.07	0.77	1.79	0.76	-
Cr	-	0.07	3.24	0.06	0.44	-
Ti	-	0.07	0.11	0.06	0.58	1.11

Of particular note is the increase in the chromium content in the weld metal to 3.24 %. This amount corresponds to the percentage of the coating in the total volume of the coated solid wire electrode.
The change in chemical composition is accompanied by a change in solidification behavior and consequently of the weld microstructure. These structural changes and the effect of the coating elements as an alloying element in the weld lead to significantly altered mechanical properties.

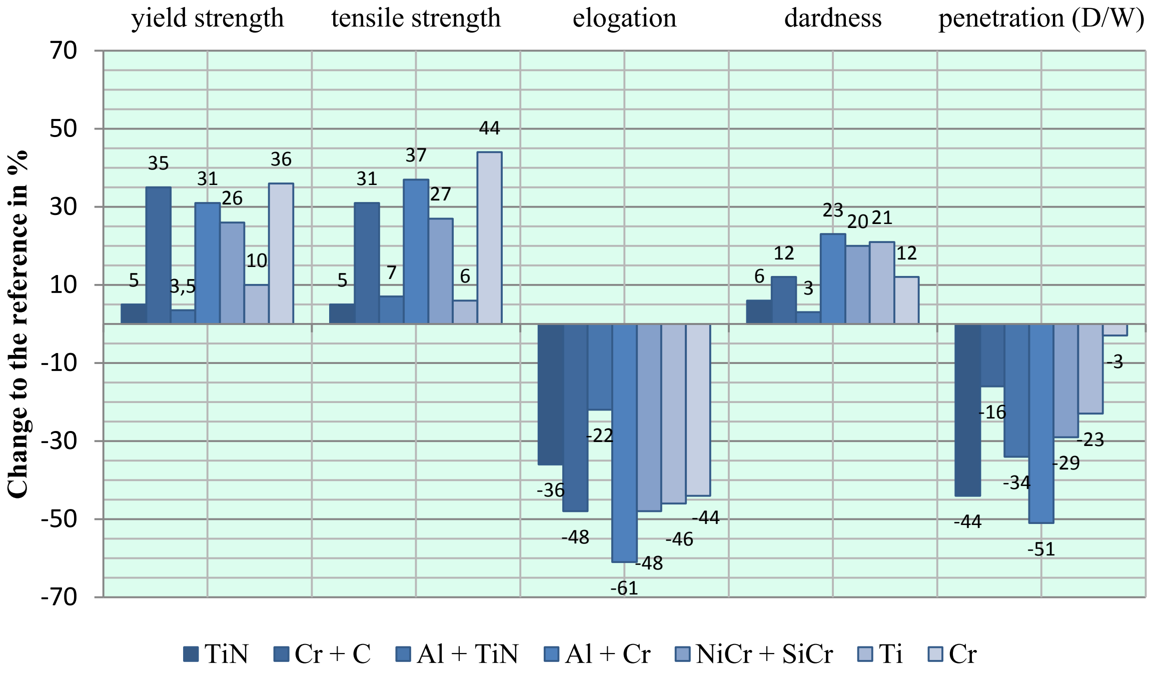


Figure 5. Mechanical properties of the weld metal and fusion penetration compared to the reference wire

Figure 5 shows the change of selected mechanical properties of the weld from the coated wire electrodes compared to the reference. It can be distinguished according to their characteristics between the titanium-containing coatings and chromium coatings.

Using titanium-containing coatings no significant increase in yield or tensile strength could be observed. However, the elongation at break decreases significantly and the hardness. This suggests the formation of brittle phases. Furthermore, by the participation of titanium, the weld penetration is considerably changed. This is evident by the decrease of the ratio D / W in the coating with TiN by up to 44 % with pure Ti and up to 23 %. Where D is penetration width and W is the penetration depth.

Under the use of chromium-containing coatings on the solid wire electrodes a significant increase in the yield and tensile strength of the weld metal was found. This increase can reach 44 % using a layer thickness of 15 microns. The elongation at break decreases significantly, but remains in areas which comparable high strength steels show. According to this fact chromium coated welding consumables could possibly used for high strength steels. Since the penetration behavior has not been changed compared to the reference wire using the chromium-coating it can be assumed that the change in the penetration behavior, shown in **Figure 4** is attributable to the use of Al, Ni, Si, C in addition to chromium for the coatings. It follows that the carbon leads to a narrow and deep penetration, aluminum to a flattening of the weld penetration. However, these assumptions need to be verified in further studies.

Besides the strength of materials under static loading, in many cases the strength und cyclic loading is of interest and was investigated. For this purpose single staged cycling loading test were carried out on different load horizons. A method of consecutive load steps was used and offers the advantage that a lack of knowledge of the approximate location of the S-N curve in prior to the tests is possible and therefore lends itself to the characterization of the cyclical strength of the weld metal of coated solid wire electrodes. Since, as already described, the coatings can be separated into two major groups in accordance with the participation of chromium or titanium, the cyclic tests were performed for coatings without any additional elements beside pure chromium or titanium. For determining the cyclical strength tensile specimens were taken from the three-layer deposit welding. The tension ratio for the tests was R = 0.1 and as failure criterion the complete specimen rupture was defined. The results for a survival probability of 95 % confidence interval of 75 % are shown in **Figure 6**. It shows that the fatigue strength can be significantly raised by the addition of titanium or chromium via the coating. The reference shows a value of 275 MPa stress range at $2x10^6$ load cycles. In comparison, the weld metal from the chromium or titanium coated welding wire can survive a value of 510 MPa stress range for $2x10^6$ load cycles. Furthermore, it is conspicuous that the low cycle fatigue strength is by the addition of titanium only at 600 Mpa stress range and thus results in a very shallow S-N curve with an slope exponent of k = 54. In contrast, the weld metals with added chromium behave similar to the reference. The slopes of the curves are nearly identical. The cyclical strength will be significantly raised by chrome in all the area, so that in the low cycle fatigue strength is approximately 820 Mpa in stress range.

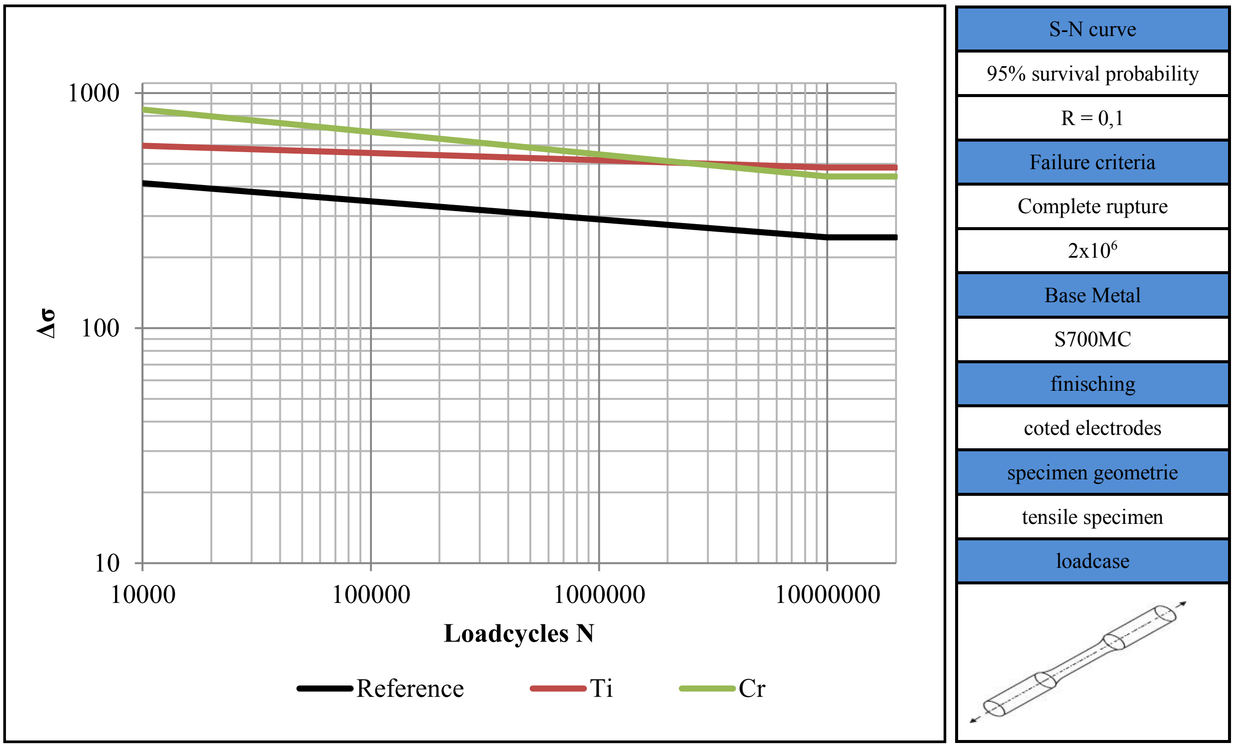


Figure 6. S-N curves of weld metals of different coated solid wire electrodes

4. Conclusion

Like postulated, a significant influence on the welding process and the mechanical properties of the weld metal can be applied by the deposition of thin film coatings on the welding wire surfaces.
Chromium-containing coatings on solid wire electrodes reduced the arc length significantly. Furthermore they increased the yield and tensile strength up to 44 %. The cyclical strength of the weld metal was increased significantly as well. The elongation at break decreased.
Titanium-containing coatings reduced the penetration ratio to 56 %. A pronounced increase of the yield strength and the static tensile strength could not be seen. In contrast, however, a significant increase in strength und cyclic loading was observed.
Finally, it should be noted that these studies contribute to the knowledge of the targeted modulation of the mechanical properties of weld filler by functional thin film coatings. Further studies on the influence of these thin film coatings on the arc plasma, the micro structural changes and the underlying effects as well as the characterization of these influences by further coating elements should follow.

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